International MUON Collider Collaboration

BERKELEY LAB
Lawrence Berkeley National Laboratory

Muon Collider:
innovative detector R&D needs and opportunities

Simone Pagan Griso (LBNL)
on behalf of IMCC

CPAD 2024

November 21st, 2024
Knoxville, TN

Muon Collider: the path to new high energy scales

The P5 report has set a new aspirational scale for high-energy exploration: 10 TeV

> *"[...] we recommend targeted collider R&D to **establish the feasibility of a 10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. [...] can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.*
>
> [P5 Report]

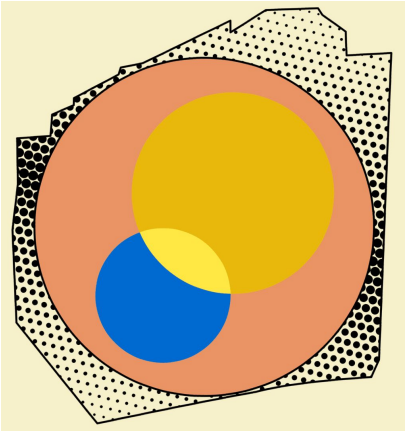
Recognized as well in the previous European Strategy, new input in preparation.

International MUON Collider Collaboration

- international effort
- > 70 institutions
- bringing together accelerator, instrumentation and theoretical physicists.

https://muoncollider.web.cern.ch/

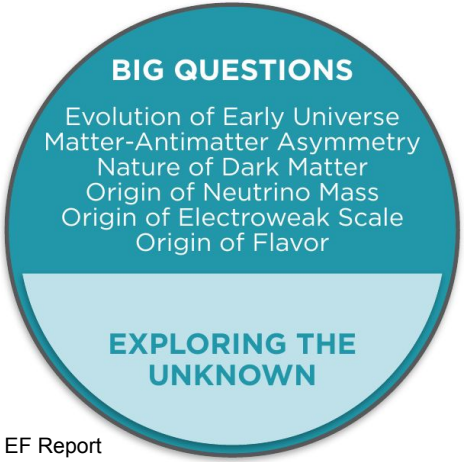
Fermilab, Aug 7th-9th 2024,
indico.fnal.gov/e/usmc2024



- US community workshop at FNAL
- 274 (+25 remote) registered; ~230-240 attended in-person

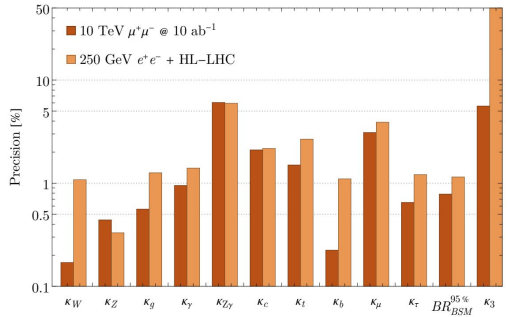
The physics we dream of discovering

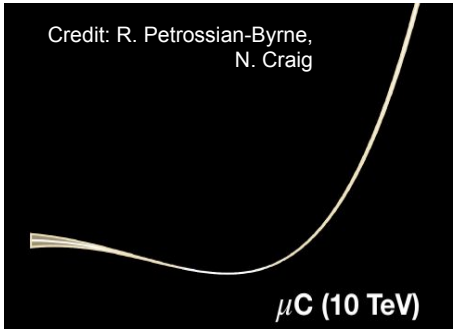
A multi-TeV muon collider is a **powerful**, **scalable** and **flexible** experimental setup to unlock answers to very profound questions.

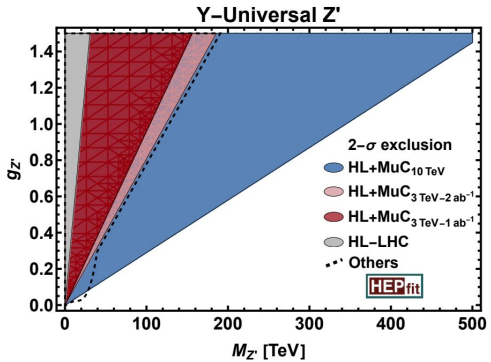


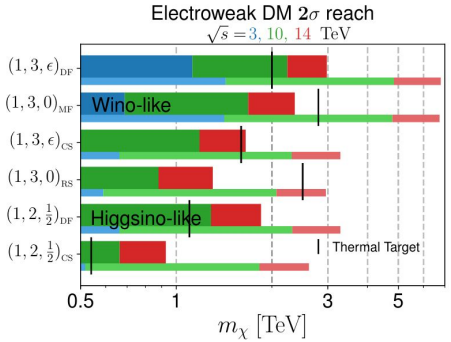
Content: Snowmass EF Report
Alternative design by T. Holmes

It will be, at the same time, a **discovery** and **precision** measurements machine.









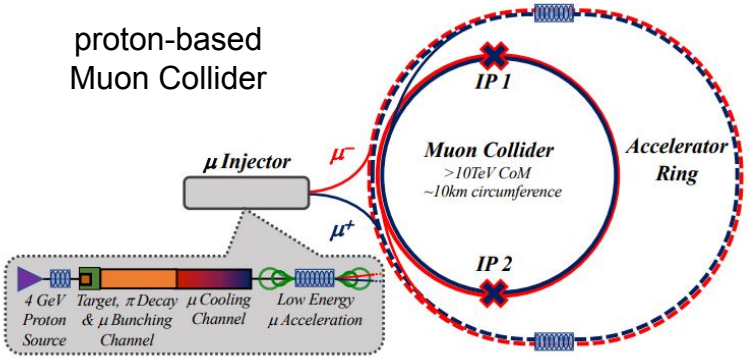
arXiv:2209.01318, arXiv:2203.07351, arXiv:2303.08533, arXiv:2407.12450

Key Accelerator Parameters & Footprint

Accelerator & Detector Parameters: 2411.02966

End-to-end design with site considerations at CERN and Fermilab

- possibility of staging in energy (3 → 10 TeV) or luminosity



Collision c.o.m. Energy	3 TeV	10 TeV
Target Luminosity	1 ab^{-1}	10 ab^{-1}
Bunch crossing ΔT	~10 **μs**	~30 **μs**
Bunch length (space/time)	5 mm / << 1 ns	1.5 mm / << 1 ns

Design fully driven by the short muon lifetime

Key challenges have been identified and (multiple) conceptual solutions have been proposed. **No fundamental show-stopper**, and redundant options.

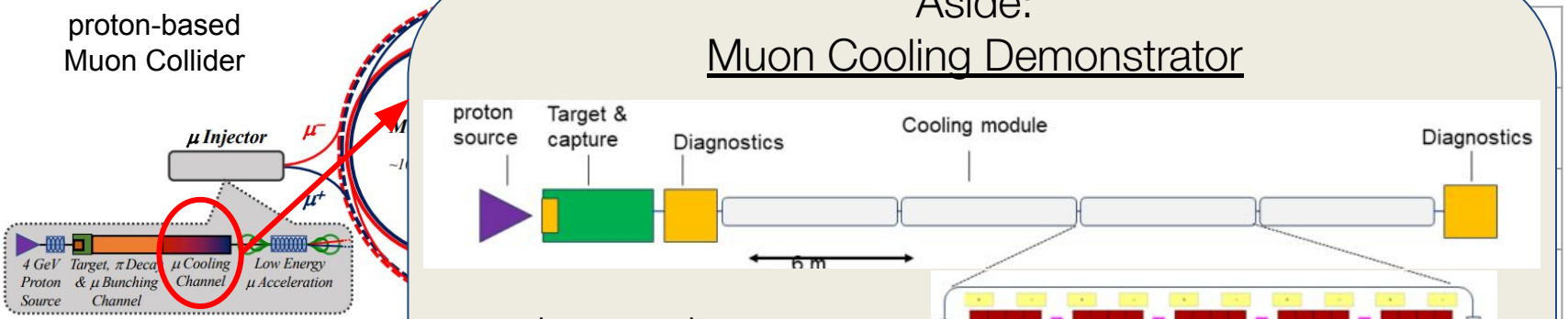
Key Accelerator Parameters & Footprint

Accelerator & Detector Parameters: 2411.02966

End-to-end design with site considerations at CERN and Fermilab

- possibility of staging in energy (3 → 10 TeV) or luminosity

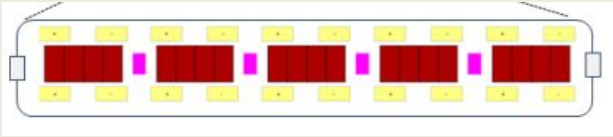
proton-based Muon Collider



Des

Key challenges have bee
proposed. **No fundamental show-stopper**, and redundant options.

Aside: Muon Cooling Demonstrator



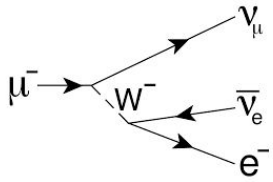
- key accelerator technology to demonstrate
- **detector diagnostic** needs intersect expertise of this community!

Dedicated CPAD talk by S. Jindariani

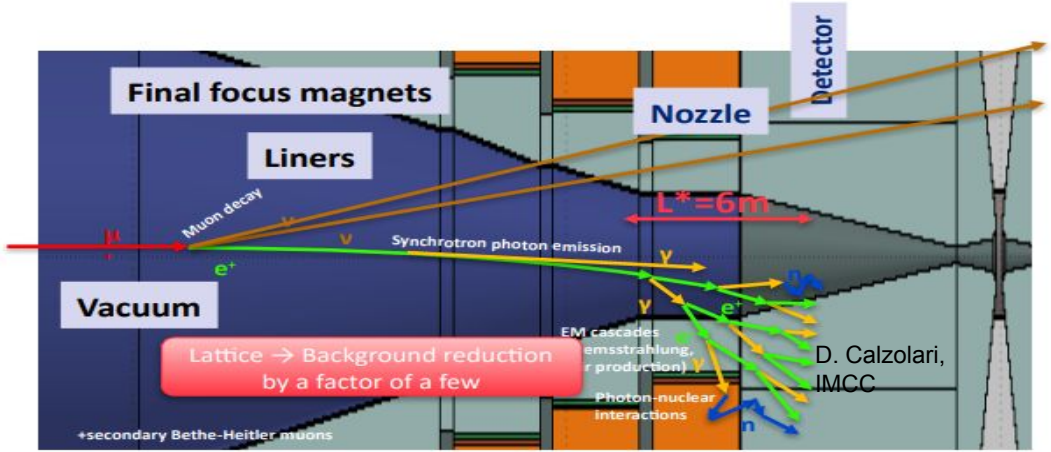
Workshop @ FNAL
https://indico.fnal.gov/event/64984/

Beam-Induced Backgrounds (BIB)

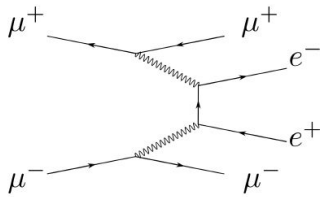
Muon beam decays



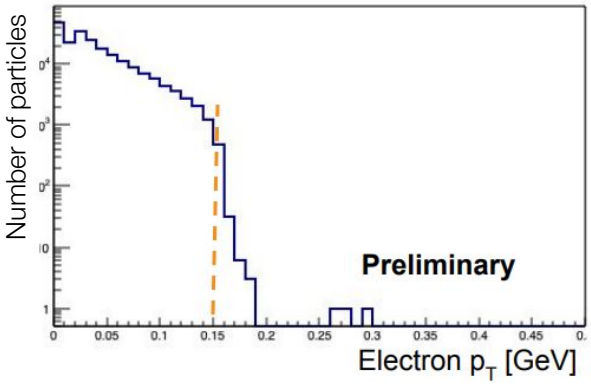
Very high-energy electrons then interact with surrounding material; relevant decays for the detector can be produced 10s of meters away.



e+e- pair production

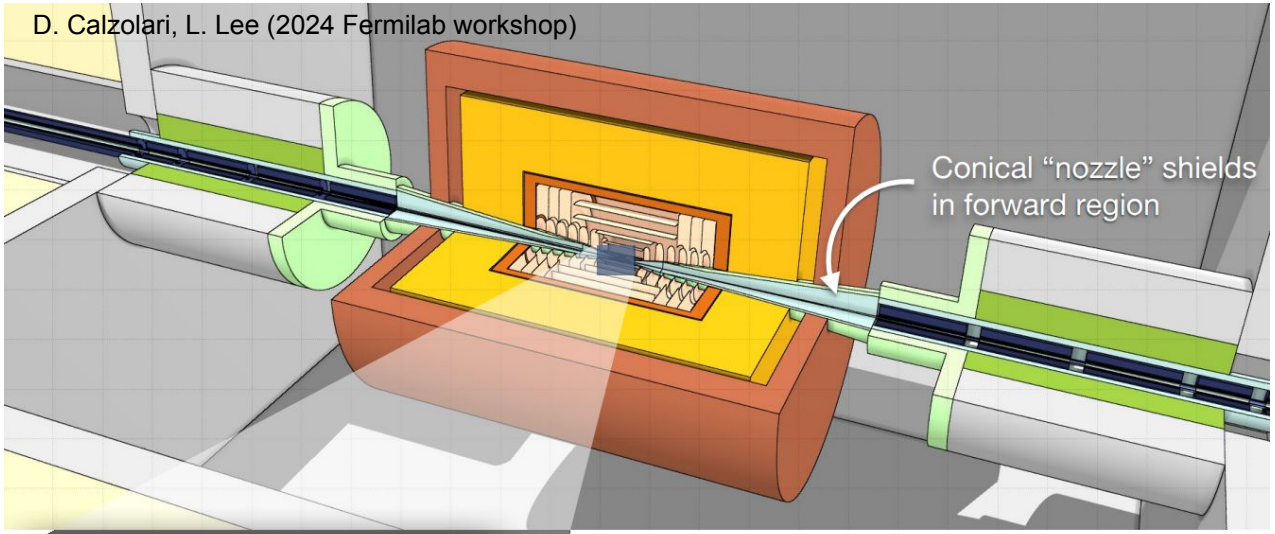


Low-energy e^+e^- pair production from beam-beam interactions; produced at the interaction point.

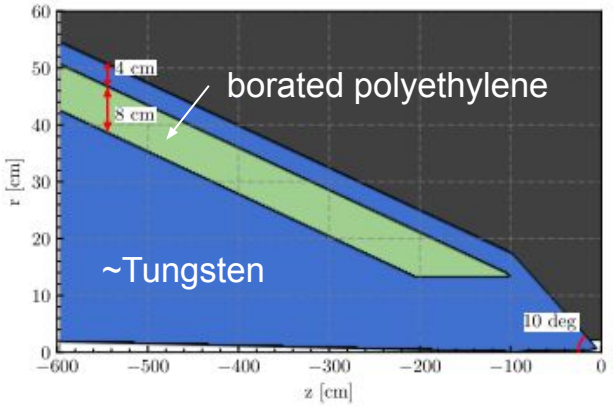


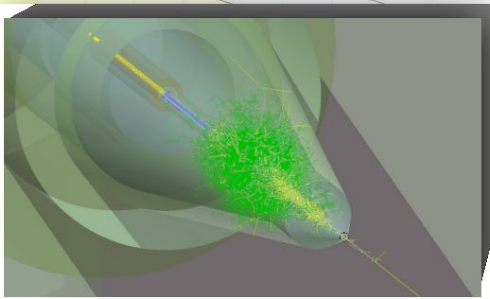
Detector shielding

Dedicated shielding to absorb high-energy electrons from muon decays



Tungsten “nozzle” (shielding)





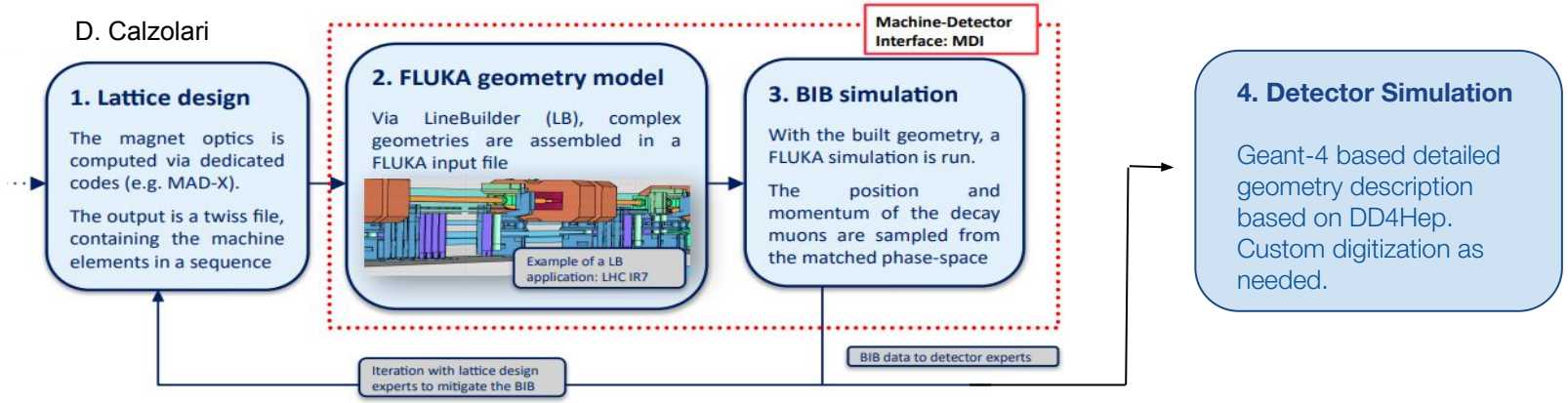
Particle production from single muon decay 25m away. Nicely absorbed by nozzle.

Now imagine ~10M of these decays…

A mechanical engineering challenge in construction, support and integration.

BIB simulation

Detailed simulations to assess the environment around the interaction point



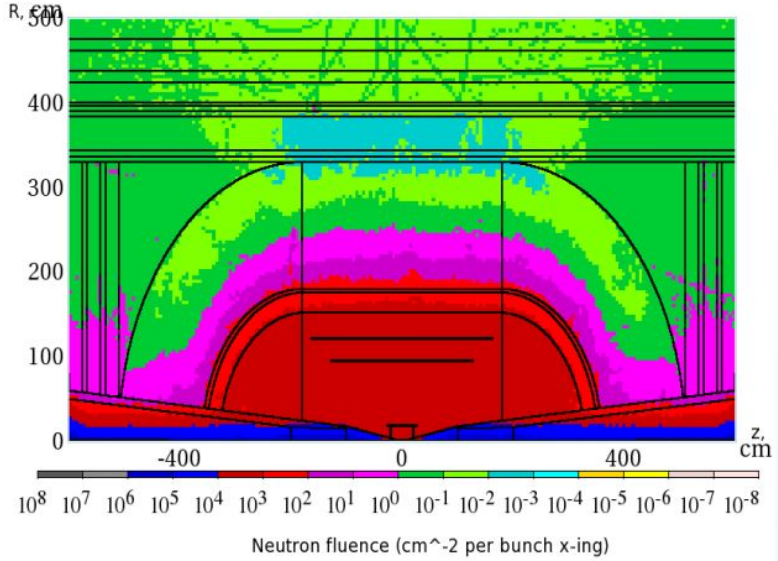
- Large flux of e/γ and neutrons
- ~ constant with collider energy
  - muon lab-frame lifetime
  - primary electron energy

Monte Carlo simulator	FLUKA	FLUKA
Beam energy [GeV]	1500	5000
μ decay length [m]	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadrons ($E_{h^\pm} > 0.1$ MeV)	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

BIB characterization

Radiation maps of the detector

- comparable or lower radiation environment with respect to HL-LHC



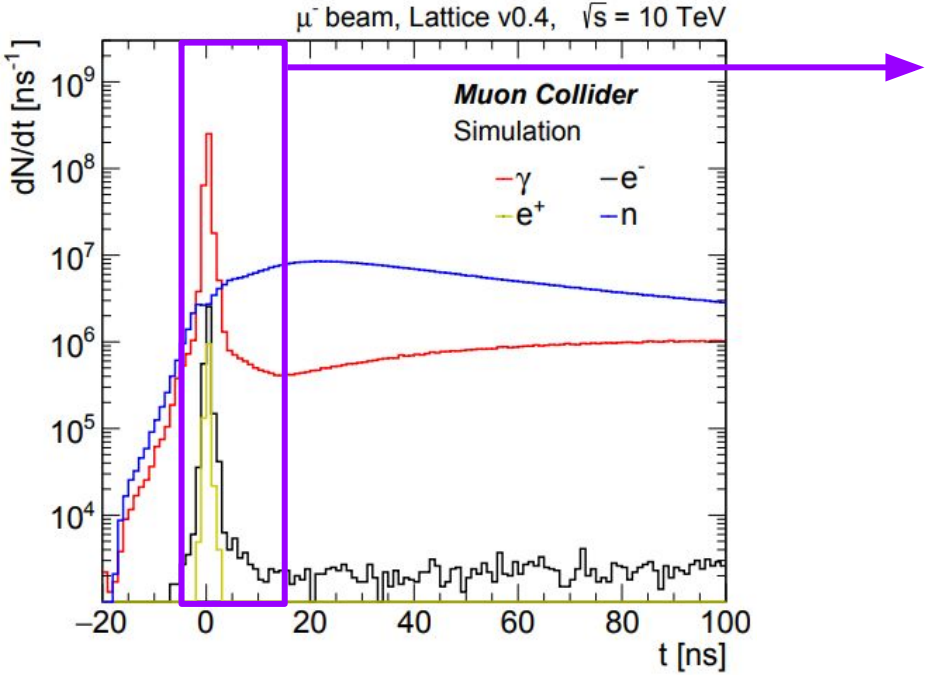
	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

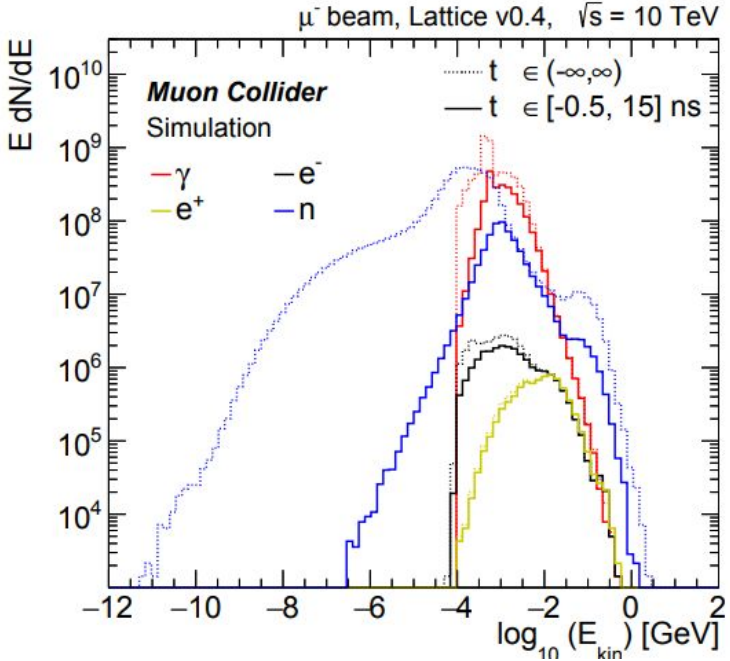
BIB characterization

Dedicated CPAD talk by K. Kennedy

Long tails can be suppressed by detectors with precise timing (10-100 ps)
Remains a cloud of low-energy particles

- Mostly electrons and photons

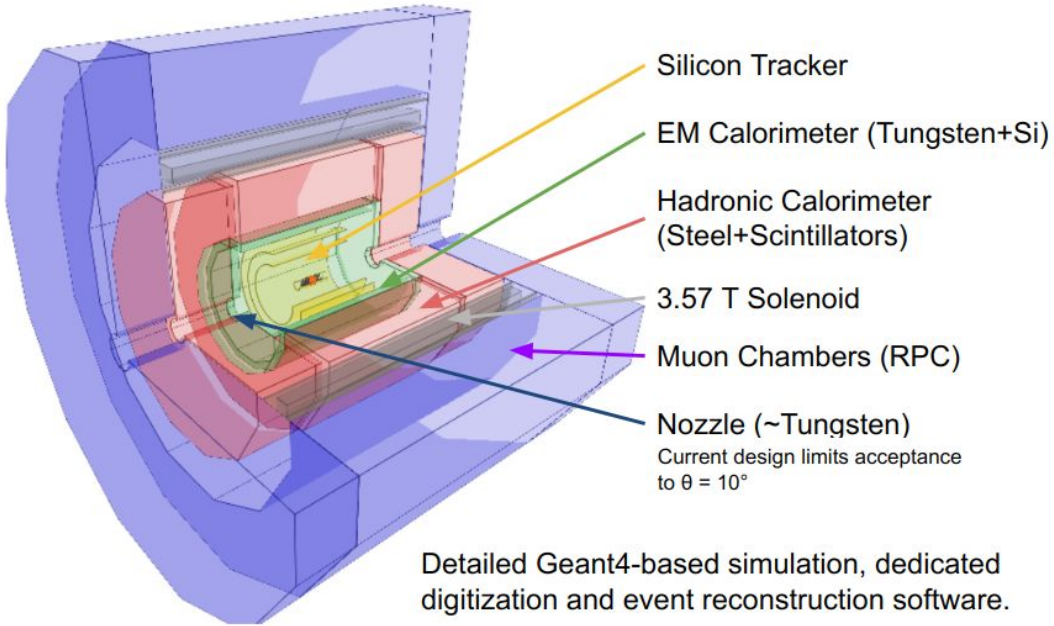




Muon Collider Detector Design

The detector is our interface between collisions and the physics we are after.

- Is it possible to design a detector capable to unlock the promising physics behind multi-TeV muon-muon collisions?
- What technology needs to be developed and what challenges overcome?



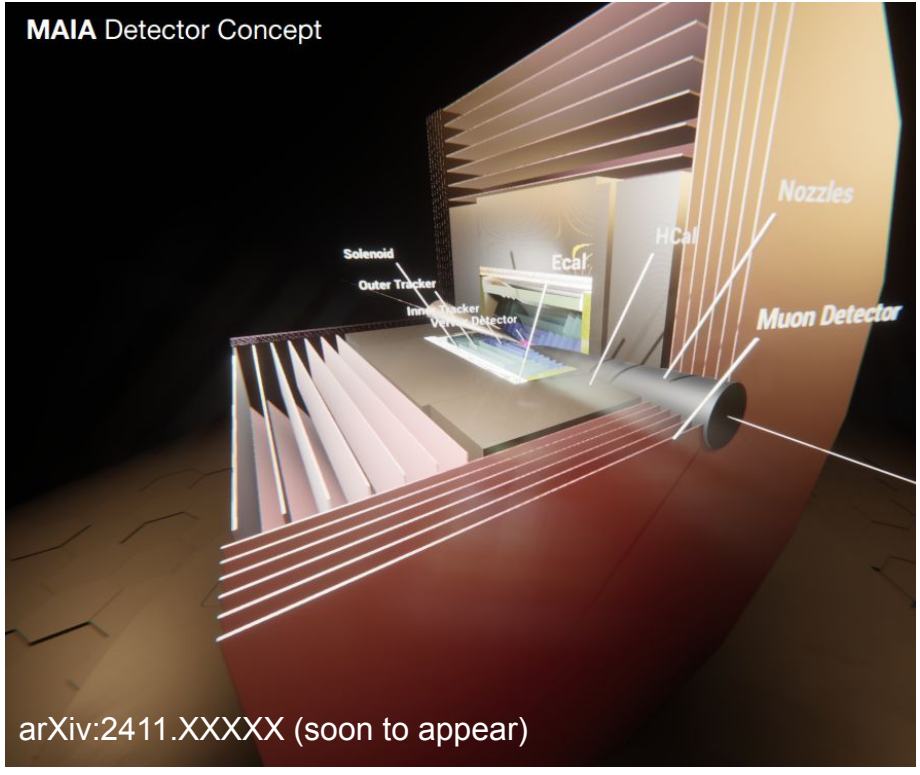
Detailed Geant4-based simulation, dedicated digitization and event reconstruction software.

- Initial concept adapted from CLIC for a 3 TeV Muon Collider
- Software suite for simulation, digitization, reconstruction
  - detailed digitization as needed to study viable technologies
  - realistic prototypes of dedicated reconstruction algorithms
  - ILCSoft → Key4HEP
- Overlay of realistic BIB simulations

10 TeV detector concepts

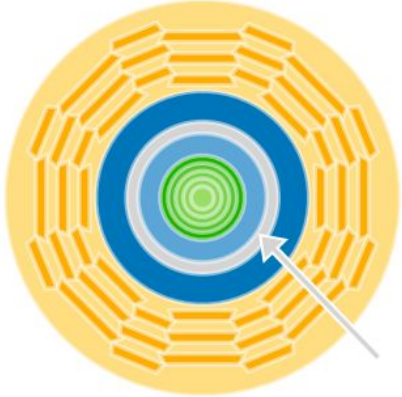
Lots of community interest!
Test several detector concepts in the 10 TeV environment

Dedicated CPAD talk by B. Roser



10 TeV MUSIC Detector

Solenoid between ECAL and HCAL



10 TeV MAIA Detector

Solenoid inside Calorimeters

Some highlights:

- Shielding reoptimization
- Tracker layout optimization
- Solenoid strength / position / description
- Calorimeter technology and dimensions

Tracking Detectors

Exploring all-silicon tracker layouts.

- other options could be explored!

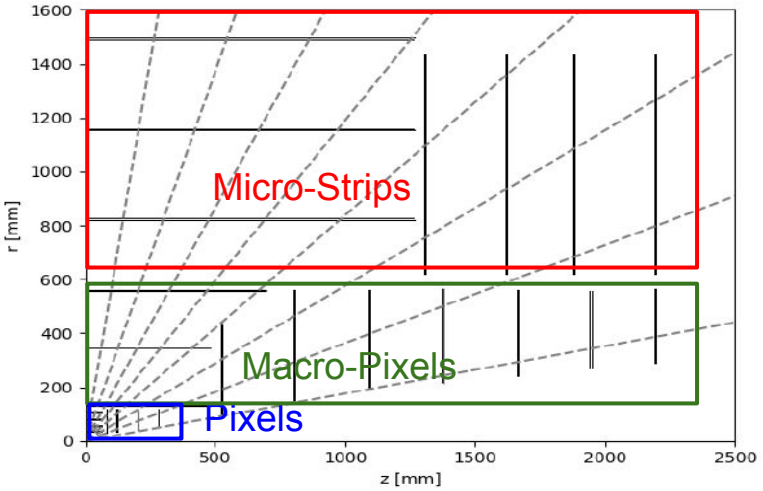
BIB manifests as cloud of hits from many low-energy particles.

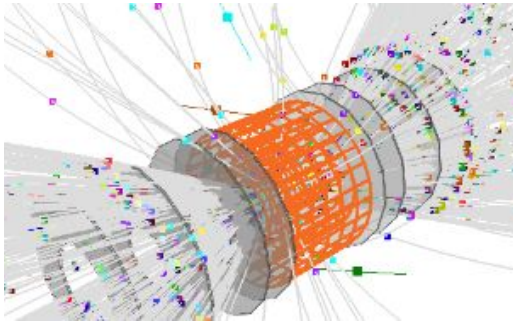
- a challenge for both detector readout as well as track reconstruction

Detector	HL-LHC Hit Density [mm^{-2}]	Muon Coll Hit Density [mm^{-2}]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.22	0.51
Strip Layer 1	0.003	0.03

Hit density per bunch-crossing, after timing selections

Bunch crossing rate ~100kHz (MuC) vs ~40MHz (LHC)





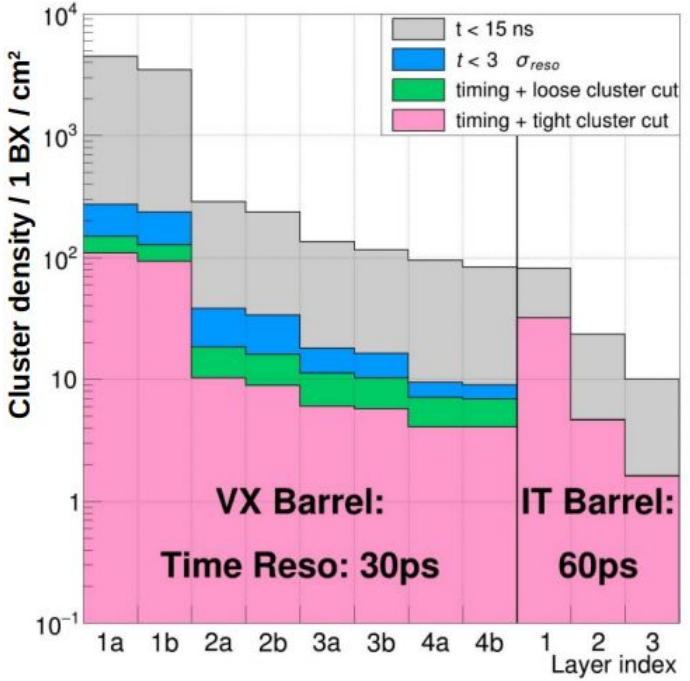
Reducing impact of BIB in the Tracker

Key handles for discrimination:

- Precision timing
- Directional information
  - cluster shape analysis
  - close-by (~mm) layers
- Energy deposition

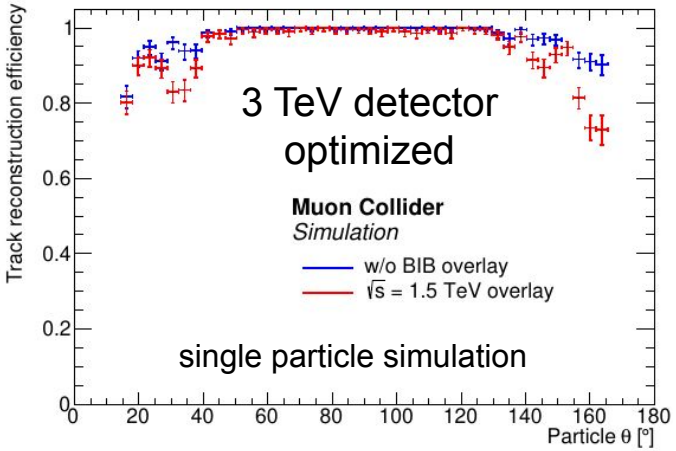
High-granularity and precision timing tracking detector
→ **4(/5)D Tracking is a requirement!**

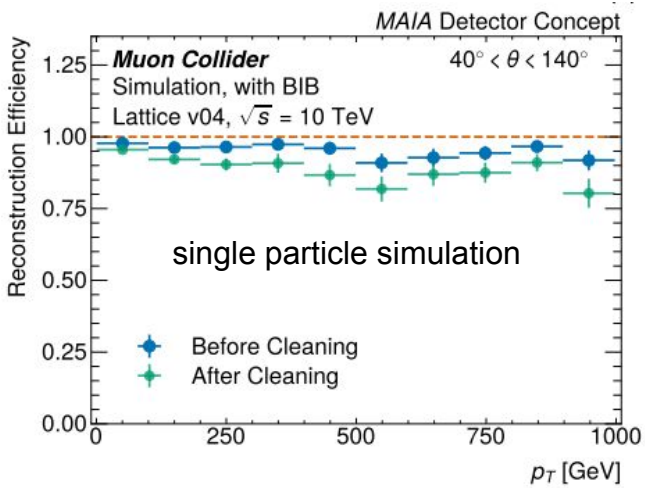
Sub-Detector MAIA/MUSIC	Technology	# Layers /Rings	"Cell" Size	Sensor Thickness	Hit Time Resolution	Signal Time Window
Units			μm^2	µm	ps	ns
Vertex Barrel	Pixels	4*/5	25 x 25	50	30	[-0.18, 15.0]
Vertex Endcap	Pixels	4	25 x 25	50	30	[-0.18, 15.0]
Inner Barrel	Macro-Pixels	3	50 x 1000	100	60	[-0.36, 15.0]
Inner Endcap	Macro-Pixels	7	50 x 1000	100	60	[-0.36, 15.0]
Outer Barrel	Macro-Pixels	3	50 x 10000	100	60	[-0.36, 15.0]
Outer Endcap	Macro-Pixels	4	50 x 10000	100	60	[-0.36, 15.0]



Tracking Algorithms

Successfully demonstrated LHC-style algorithm optimized for this environment can successfully disentangle signal from beam-induced backgrounds.



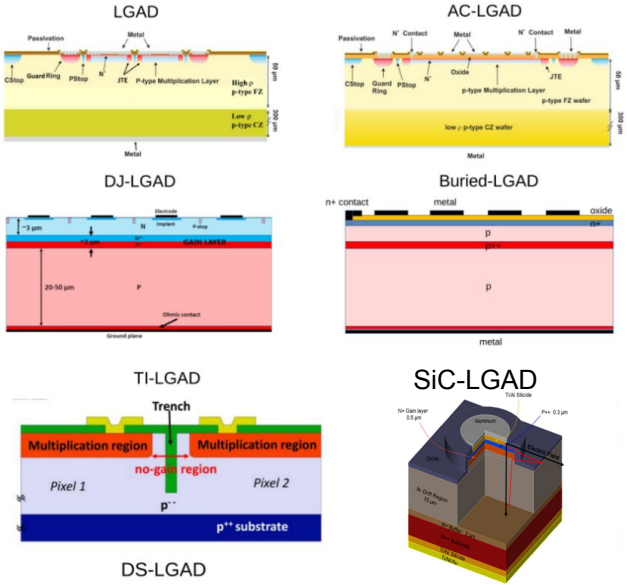


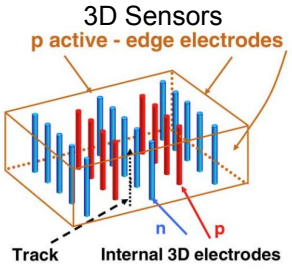
- Modern and well-maintained code libraries: ACTS
- Still computational challenging: O(mins)/event
- BIB/fake tracks from 100k / event to O(1) / event after quality selections

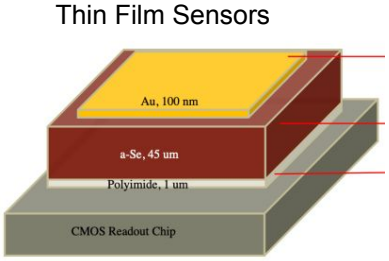
Tracker Sensor Technology

A rad-hard, granular and precision-timing capable sensor!

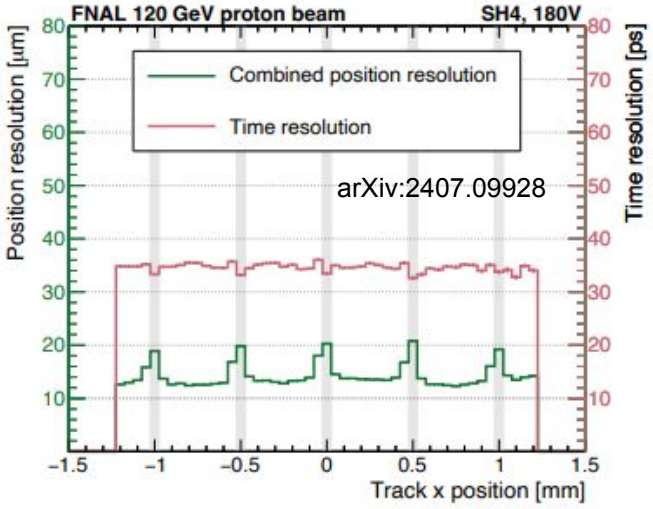
- multiple technologies that can evolve to meet those requirements
  - many based on LGAD, but also 3D sensors, wide band gap materials, …
- synergy with HL-LHC and other projects







One example:
Long AC-LGAD Strip sensor

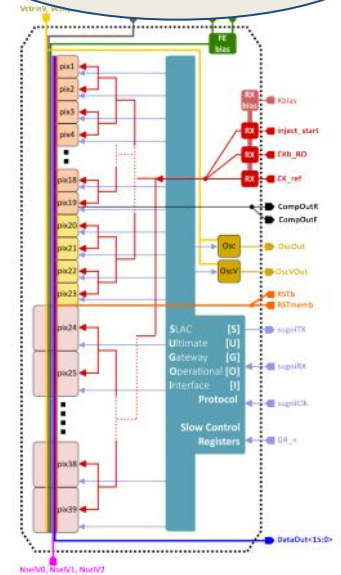


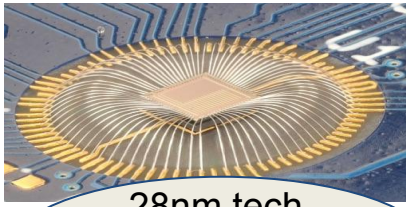
Tracker Front-end Electronics

Dedicated CPAD talks by T. Heim, also B. Markovic, J. Sorenson, C.Mills, …

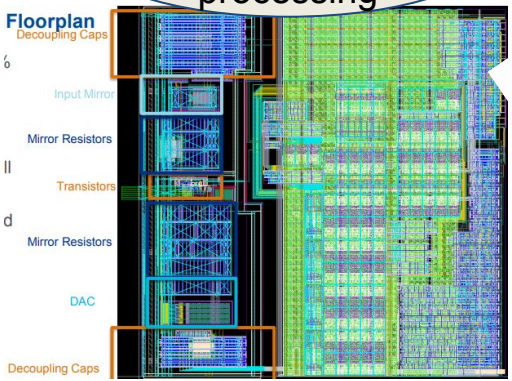
Several new or fundamentally different features in a tracker FE electronics

low-power TDC for "*every*" channel

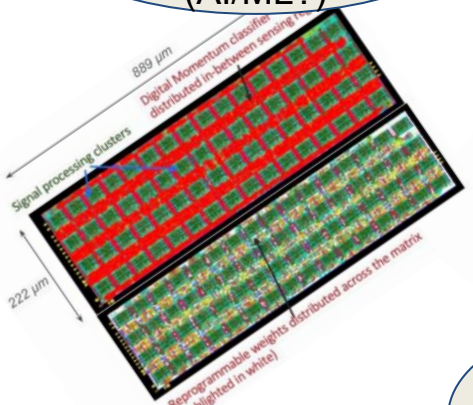


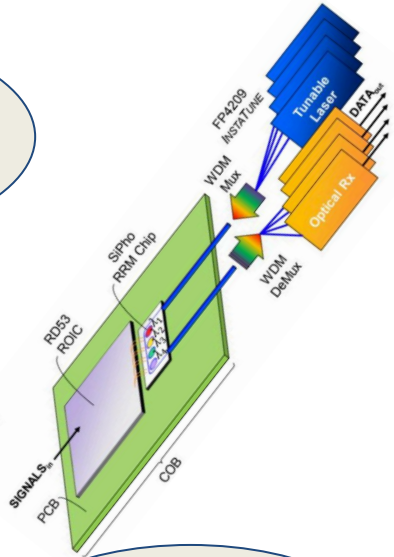


28nm tech, memory -> processing



on-chip filtering / sampling / selective powering / (AI/ML?)



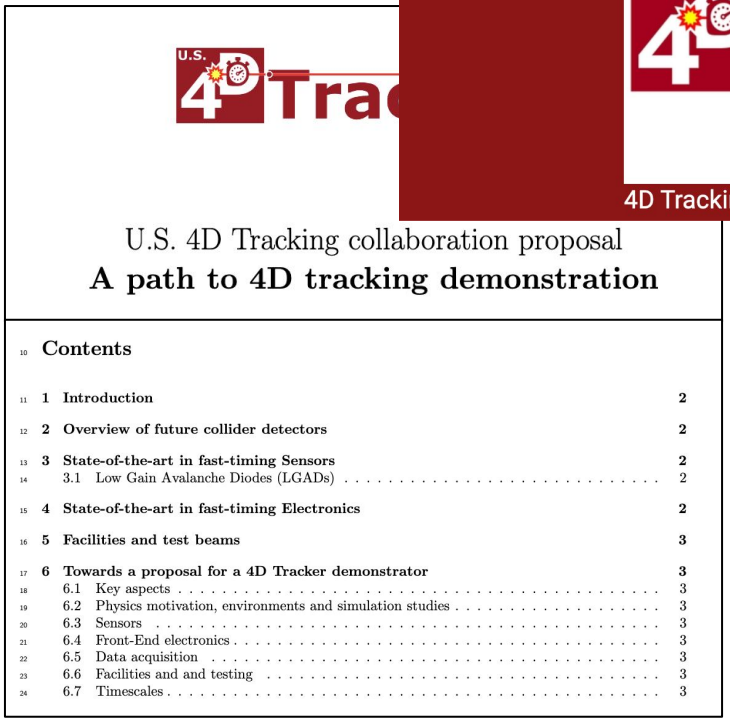


triggerless and high-bandwidth data transmission

4D Tracking Demonstrator?

Dedicated CPAD talk by
A. Schwartzman

Moving from single prototypes to (small) integrated systems adds significant complexity, but necessary in learning to build functional large-scale detectors.



U.S. 4D Tracking collaboration proposal

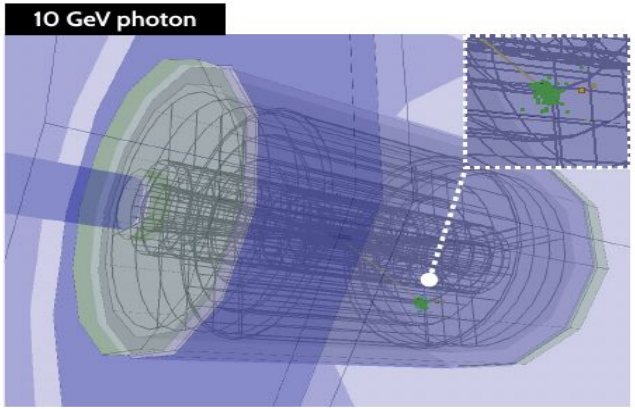
A path to 4D tracking demonstration

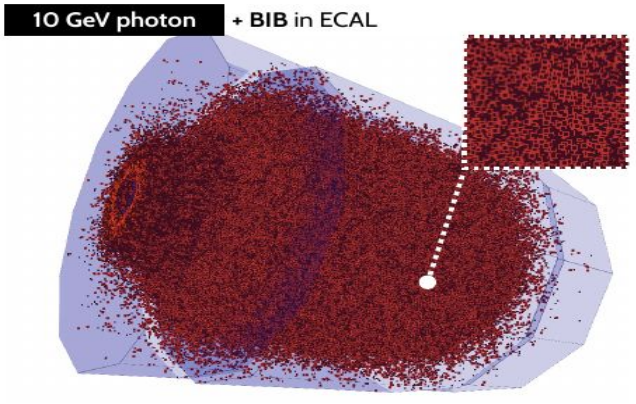
Contents

- Simulation, reconstruction, and applications
- Sensors
- Electronics
- Facilities / Test beam
- Collaboration proposal

Calorimeters

Diffuse Beam-Induced Background energy deposits in both electromagnetic and hadronic calorimeters.





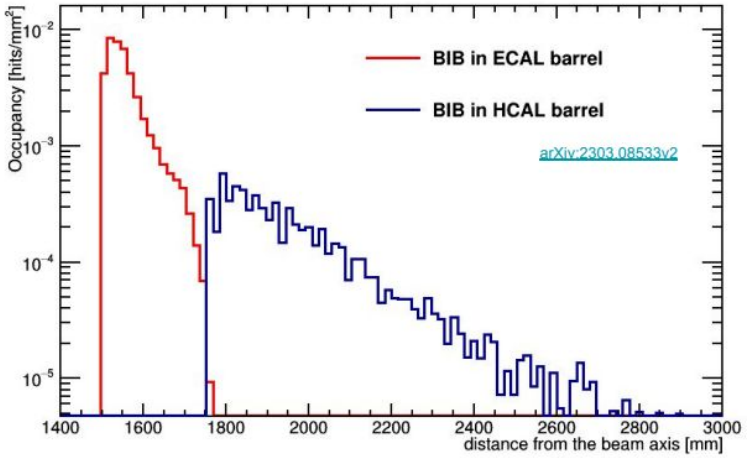
Somewhat similar in nature to what we're learning to deal with for HL-LHC.

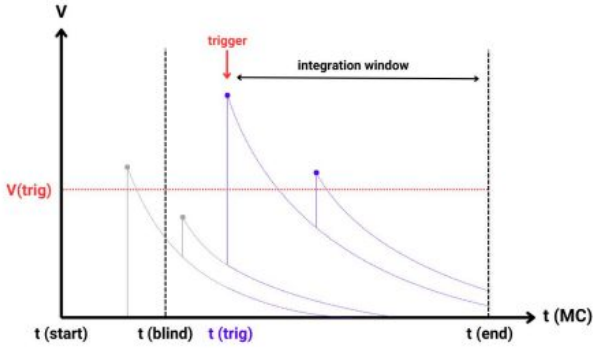
- learning how BIB is kind-of LHC pile-up.. until it's not

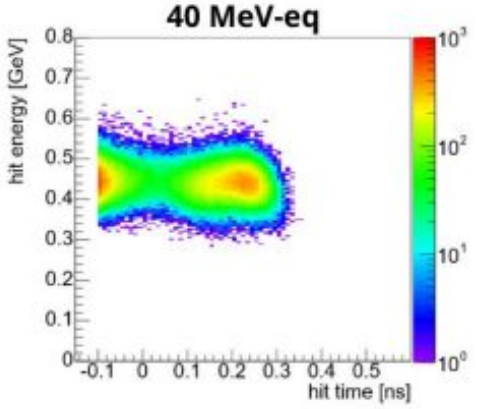
BIB impact in the Calorimeters

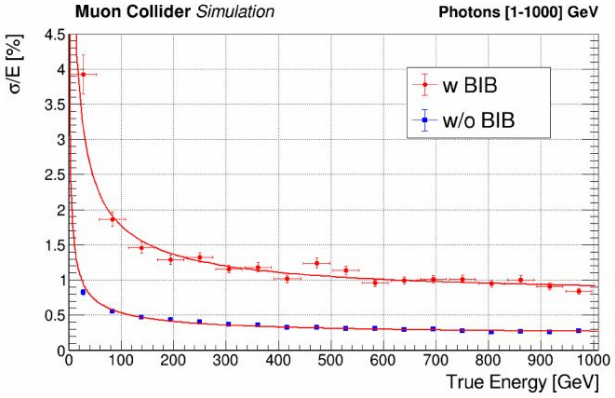
Most BIB energy deposited in first layers
- particularly severe for the EM calorimeter
- longitudinal segmentation critical

Realistic modeling of signal formation for various technologies to understand full impact.





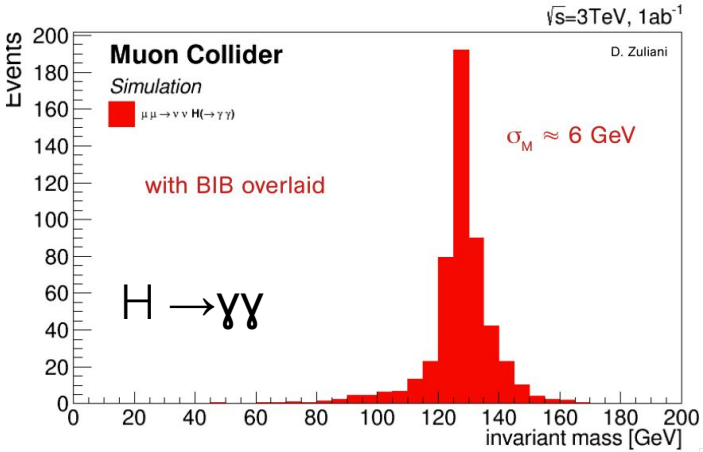


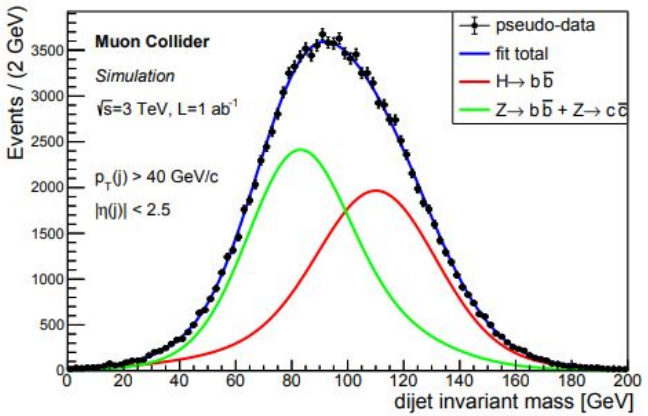


Calorimeters needs and performance

Key detector characteristics:

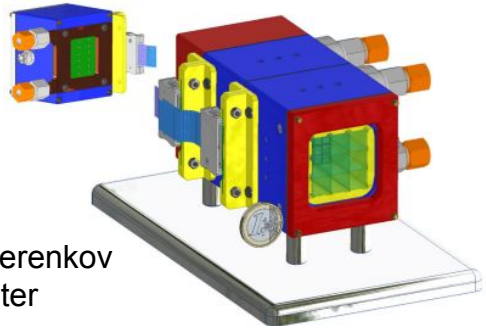
- large dynamic range – physics needs
- short integration time
- good time-of-arrival resolution
- longitudinal segmentation
- good radiation hardness
- good energy resolution for physics.





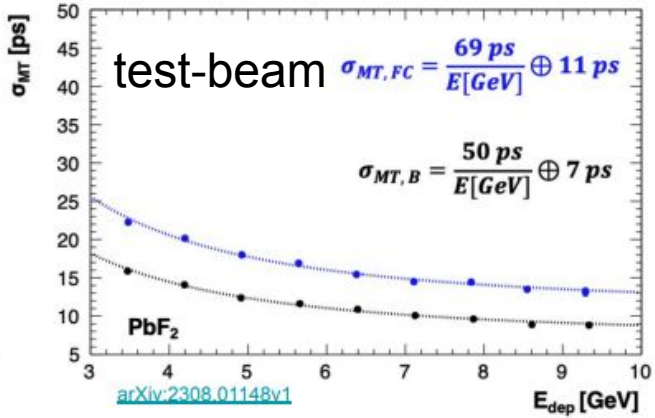
Calorimeter Technologies: e.g. EM calorimeters

Both homogeneous and sampling calorimeters being considered



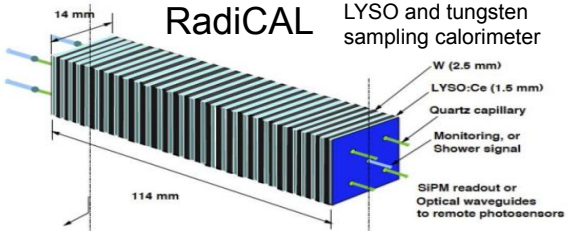
Crilin
PbF2 Cherenkov Calorimeter

Sub-Detector MAIA / MUSIC Units	Technology	Cell Size mm^2	# Longitudinal Slices	Time Resolution ps	Integration Time ns	Signal Time Window ns
EM Cal - Barrel	W+Si / Crystal	5 x 5	50 / 6	/50	/25	[-0.25, 10]
EM Cal - Endcap	W+Si / Crystal	5 x 5	50 / 6	/50	/25	[-0.25, 10]
HAD Cal - Barrel	Iron + Scint.	30 x 30	75 / 70	–	–	[-0.25, 10]
HAD Cal - Endcap	Iron + Scint.	30 x 30	75 / 70	–	–	[-0.25, 10]

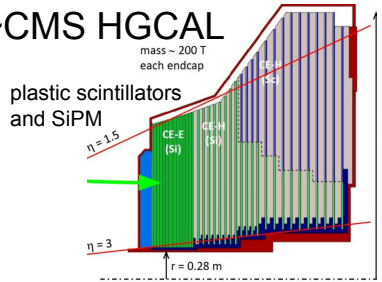


Many more other options being developed that could and should be considered!

RadiCAL
LYSO and tungsten sampling calorimeter



~CMS HGCAL

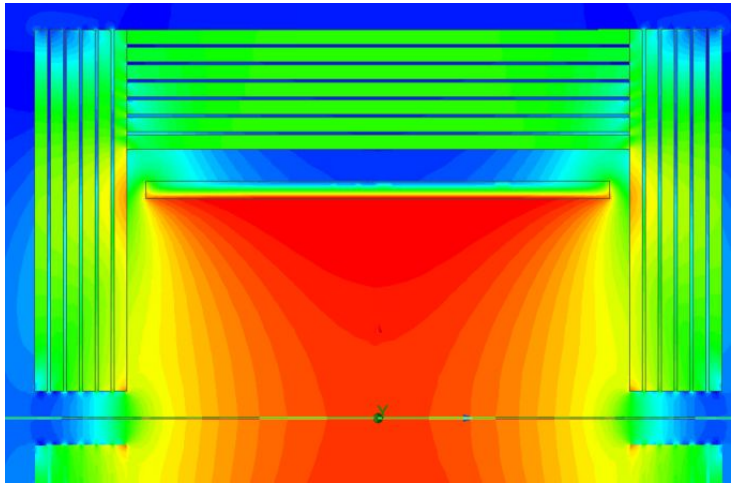


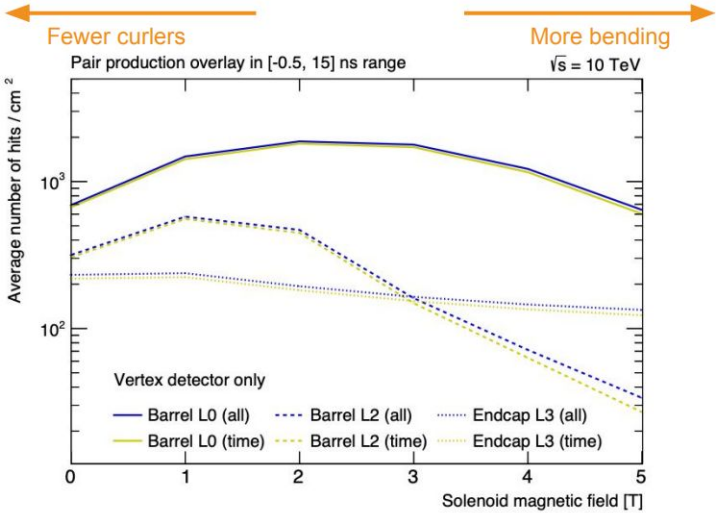
Solenoid

Large aperture and high field solenoids are complex objects that take many years to design and manufacture!

- baselined 10 TeV detector with 5 T solenoid
- momentum resolution to high-pT particles, reduction of incoherent e^+e^- pairs

Initial studies on realistic field maps and geometry implementation.

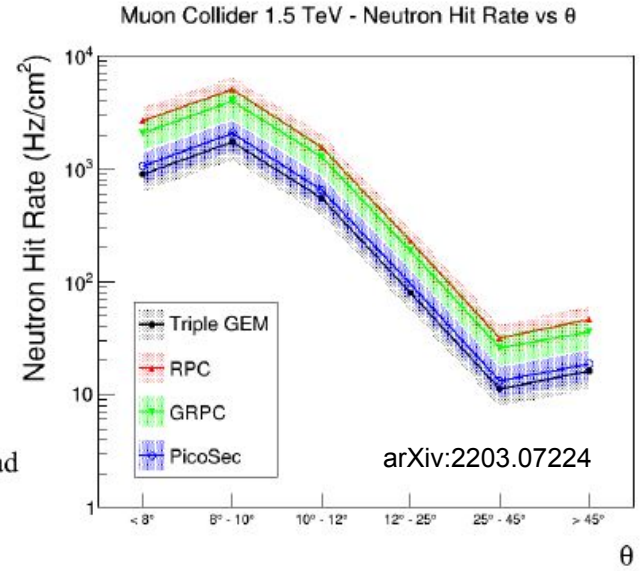




Muon Detection

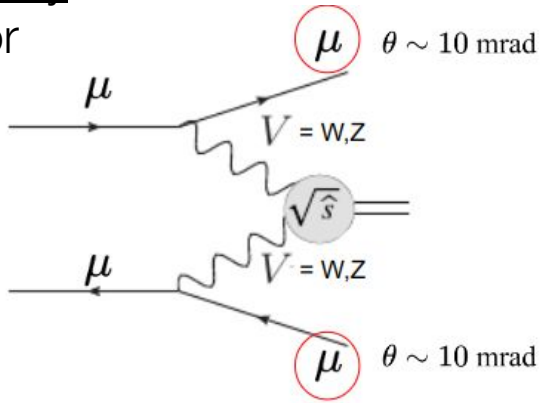
Much reduced BIB flux, within reasonable readout window
Several technologies being compared

- also considering removing and using highly segmented calorimeters as muon “taggers”



Physics case established to tag very forward muons; complex detector concept

- through shielding
- very high-radiation
- complex readout



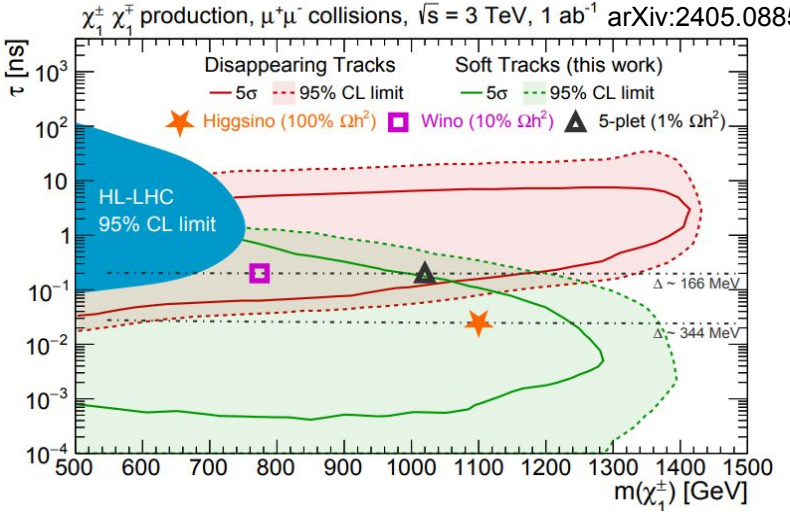
Connect back to physics!

Full simulation studies

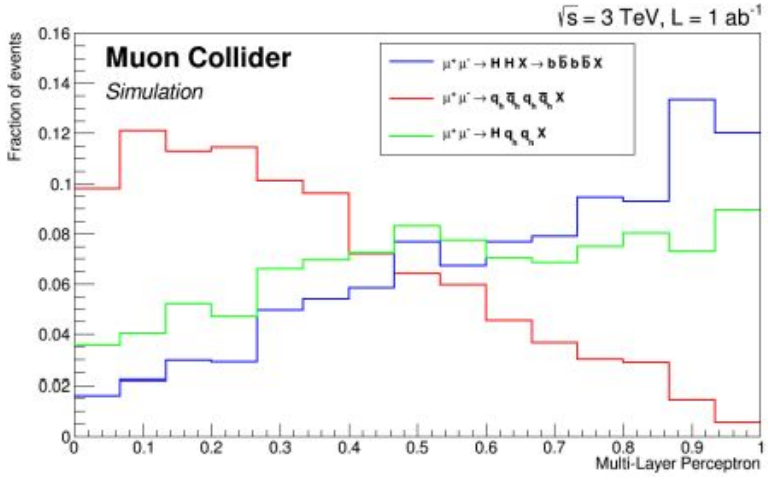
- understand overall detector performance
- validate fast-simulation studies used for building the physics case!

Cross-section measurement uncertainty

Full sim		Fast sim	
H->WW	2.9%	H->WW	1.7%
H->ZZ	17%	H->ZZ	11%
H->bb	0.75%	H->bb	0.76%
H->μμ	38%	H->μμ	40%
H->γγ	8.9%	H->γγ	6.1%



arXiv:2405.19314



Conclusions

A multi-TeV muon collider offers exciting physics opportunities

On designing a detector that excels in this unique environment:

- Phase-1: prove a minimal design that can extract the needed physics and identify possible technologies that can evolve to those needs

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  - many more details not covered here: PID, Luminosity, and much more!

Blue-sky R&D cutting across many RDC groups!

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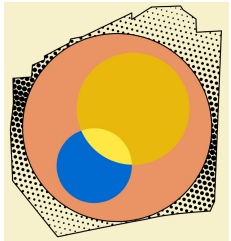
Blue-sky R&D cutting across many RDC groups!

Join a fast-growing community interested in these challenges and opportunities

International MUON Collider Collaboration

https://muoncollider.web.cern.ch/
muoncollider-detector-physics@cern.ch

Updates on US effort organization:
usmcc-info@fnal.gov



BACKUP

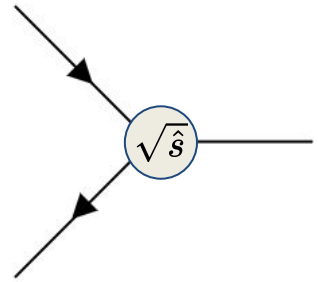
Internal Outline

- [1] Muon Collider motivation - P5 + organization
- [1] Physics motivation
- [1] Accelerator Design; important parameters
  - generic message on implications on detector design
- [2-3] Beam-Induced backgrounds -> ad BIB talk by Kylie
  - major factor in design of accelerator and detectors
  - source, mitigation (nozzle), characterization, (simulation)s
  - radiation damage projections
  - mechanical challenges in nozzle design -> RDCXX
- [2] Detector concepts -> ad detector performance talk(s)
  - intro, disclaimers, aims
  - simulation, digitization, reconstruction and software
- [5-6] Tracking detectors
  - strawman layout; low-level plots and BIB impact; cluster analysis (double-layer, shapes); tracking performance => requirements (see Timon's talk)
  - Sensors -> ad Sergo's talk
  - FE readout chip and DAQ -> Bojan's talk
  - 4D workshop ad and summary talk
- [4-5] Calorimeters
  - BIB longitudinal distribution and general considerations
  - EM Calo R&D options: Crilin, Si-W, … see also RADiCAL talk
  - Had Calo R&D options; segmentation, tracking
  - Jets, photons, and b-jet reconstruction
- [1] Solenoid
  - position, lack of magnetic field in MS so far?, technical challenges
- [2] Muon system
  - brief: strawman approach,
  - forward-muon [tracking] detectors challenges
- [1] Others detectors
  - PID, DAQ considerations, …
- [1] Physics simulations and results
- [1] Conclusions

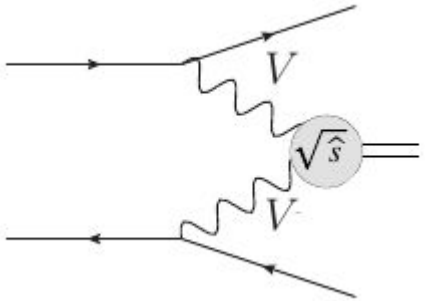
TOTAL: 22+3 slides; talk should be 25'+5' – OK

Physics at a multi-TeV Muon Collider

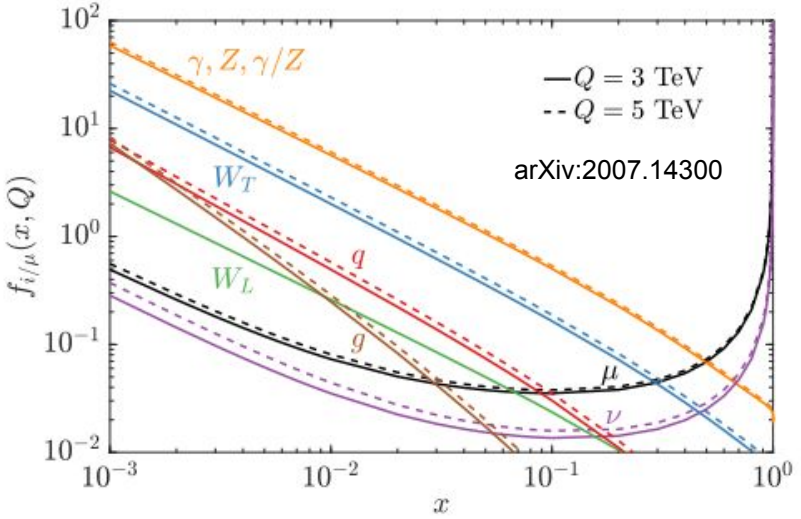
Large breadth of physics program, as needed from a big project



$\sigma \sim 1/\hat{s}$

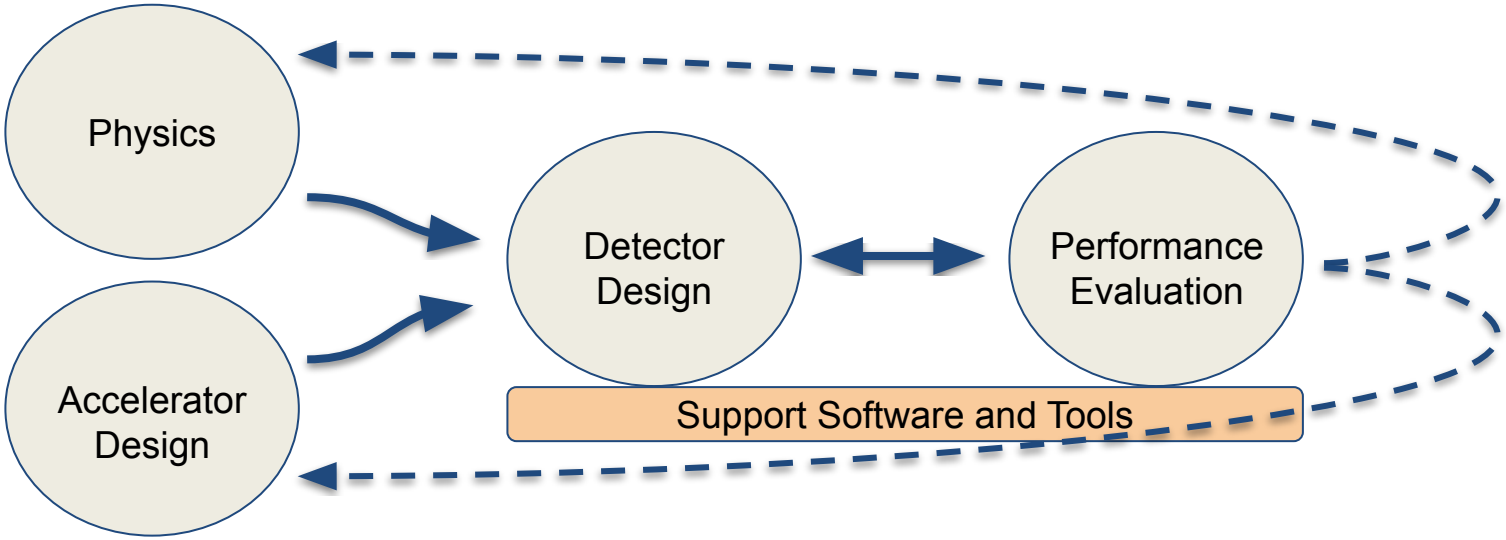


$\sigma \sim \log \hat{s}$



- ~10M Higgs bosons, small physics background => **precision Higgs** physics
- Vast program of **electroweak measurements**
  - including high precision measurement of the **Higgs potential**
- multi-TeV **discovery machine** with large direct and indirect reach **beyond LHC**

Software for detector studies



Realistic suite of G4-based simulation, digitization, reconstruction software

- based on ILCSoft, migrating towards key4hep
- full overlay of realistic BIB simulations
- detailed digitization as needed to study viable technologies

Fast DELPHES-based simulation for high-statistics physics studies.